

Dillon Reservoir, Colorado

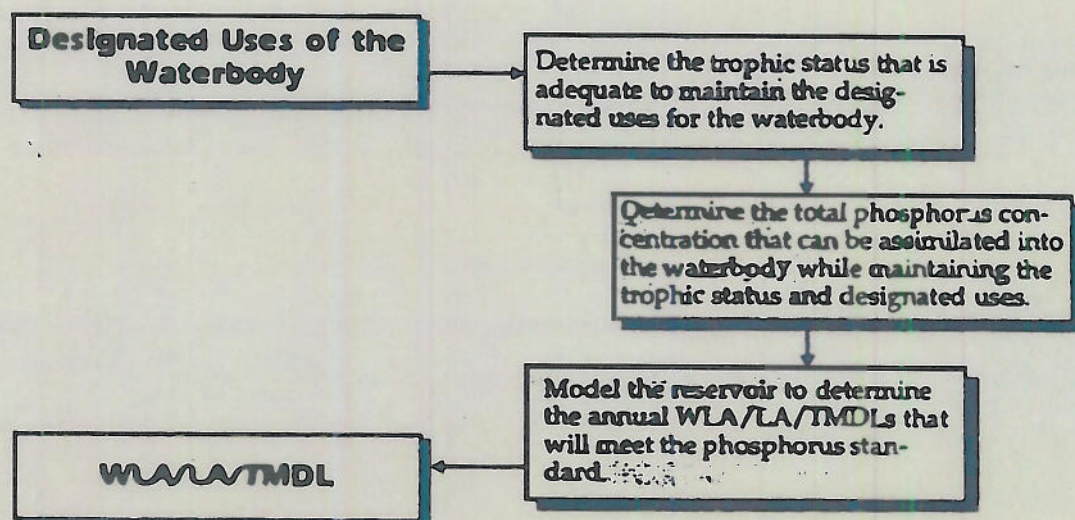
The following summary table contains a list of the key components that were used by the Colorado Water Quality Control Commission (WQCC) for developing site-specific water quality criteria for Dillon Reservoir.

Components	Values for Dillon Reservoir
Waterbody Type	man-made impoundment
Ecoregion	not given
Waterbody's Designated Use	drinking water supply, recreation, and support of coldwater aquatic life
Size of Waterbody	lake volume = 262,000 acre-feet lake area = 3300 acres
Retention Time	not given
Chlorophyll <i>a</i> Target	none established
Nutrient Standard	0.0074 mg/L total phosphorus in the top 15 meters of the water column as a growing season average
Basis for Standards	The 1981 and 1982 trophic status of Dillon Reservoir is considered adequate to maintain all existing uses over the long term. 1982 will be used as the base year when indexing future yields of phosphorus.
Water Yield for Watershed	212,000 acre-feet (1982)
Annual Load	10,162 lb/yr
Model/Analysis	The Vollenweider (1969) equation and regression analyses
Effluent Limitations	0.5 mg/L TP (daily max. conc.); new or existing facilities with discharges in excess of 2000 gallons/day. 0.1 mg/L TP (30-day average; this is also used for site approvals and permits)

Methodology Used to Derive the Criteria

Dillon Reservoir, a man-made impoundment with 3300 surface acres, serves as a water supply for over one-half of the population that is served by the Denver Water Board. The phosphorus standards are expected to protect the drinking water supply from taste and odor problems that may result from excess algae growth, and to maintain the designated uses for cold water aquatic life and recreation.

The methodology used by the Colorado Water Quality Control Commission to develop site-specific phosphorus criteria for the Dillon Reservoir is outlined below.



Phosphorus limitations were established for Dillon Reservoir to preserve and maintain the water quality that was observed in 1981 and 1982. The maximum chlorophyll *a* concentrations during July of each year fell between 11 and 13 $\mu\text{g/L}$ resulting in a mesotrophic condition that was determined by the WQCC to be sufficient to maintain all existing uses over the long term. To calculate the water quality requirements necessary to maintain the desired conditions of the lake, a water quality model was developed. The model, known as the Lake Dillon Model, had three components: (1) a land use component, (2) a trophic status component, and (3) an effects component.

The *land use component* uses input data consisting of land use, runoff and water yield information for the watershed to generate nutrient yield by segments and by sources, and loading nutrient loading. The input for this portion of the model requires a matrix of land use information consisting of the intensity of different types of use on an area or population basis for each of the 19 segments of the

watershed, the amount of gauged runoff for the year being modeled, the amount of water to be pumped or diverted from other watersheds, and the mean concentration of this pumped or diverted water on a month-by-month basis.

The *trophic status component* uses information about lake level, total monthly runoff input, and total monthly output to determine mean total phosphorus and mean chlorophyll *a* concentrations. The total phosphorus value for the trophic status component was calculated using the Vollenweider (1969) equation:

$$C_p = \frac{L_p}{z(1/t_w + s)}$$

where: C_p = phosphorus concentration of the lake
 L_p = phosphorus loading of the lake
 z = mean lake depth
 s = phosphorus sedimentation coefficient
 t_w = residence time for water

The second data output for the trophic status component generates the chlorophyll *a* value based on its relationship to total phosphorus concentration. The equation to predict chlorophyll *a* concentrations used the slope from the Dillon-Riegler equation (1974) and the observed chlorophyll *a* values to calculate the intercept. The resulting equation that was used to predict chlorophyll *a* values for the Dillon reservoir is as follows:

$$\log B = 1.449 \log(C_p) - 0.398$$

where: B = chlorophyll *a* ($\mu\text{g/L}$; July-October, 0-5 m)
 C_p = total phosphorus ($\mu\text{g/L}$; July-October, 0-15 m)

The *effects component* was based on lake and watershed nutrient yields and it determines the effects the trophic status component has on economic and aesthetically important parameters such as transparency and dissolved oxygen. Using the general slope given by Carlson (1977) and a common intercept value based on the log-transformed relationship between secchi depth and chlorophyll *a* observed in 1981 and 1982, an equation was formulated to predict secchi depth based on chlorophyll *a* concentration. The equation that was derived for Dillon reservoir is shown below:

$$\ln SD = 2.4 - 0.68 \ln B$$

where: SD = secchi depth (m)
 B = chlorophyll *a* ($\mu\text{g/L}$)

Of additional concern, is the minimum oxygen level in the deep water. For Lake Dillon, the initial oxygen concentration was assumed to be 9 mg/L, which is the saturation concentration during the spring turnover. The oxygen depletion is equal to the minimum oxygen observed toward the end of the stratification subtracted from 9 mg/L. For prediction purposes, data collected from a point located 5 m over the bottom of the index station was used. Using the degree of depletion in each of the 2 years (1981-1982) as the dependent variable and the areal hypolimnetic oxygen deficit (AHOD; mg/m²/day) as the independent variable, a slope of 0.00698 was generated. Multiplying this slope by the AHOD yields the predicted amount of depletion (mg/L). The remaining oxygen concentration is the difference between the depletion and 9.0 mg/L.

Results

The TP standard derived for the Dillon Reservoir was 0.0074 mg/L. Load estimates were developed using the watershed's 1982 water yield of 212,000 acre-feet and extrapolating a nutrient budget from monitoring data, which included significant contributions from atmospheric deposition. The estimate of the total annual phosphorus loading has been supported by comprehensive monitoring of stormwater, dry weather discharges, estimated septic tank leakage/loadings, and land use-specific monitoring. The total annual phosphorus loading for Dillon Reservoir was established at 10,162 pounds.

In any consecutive 12-month period, the total annual discharge of phosphorus from municipal and domestic sources with flows greater than 2000 gallons per day into the Dillon Reservoir watershed is not to exceed 1577.6 lb/yr. This phosphorus discharge has been allocated among 4 major municipal facilities and 16 minor domestic discharges. The remaining 8584.4 lb/yr has been allocated to other unspecified point and nonpoint sources of phosphorus.

Municipal/domestic point sources; (flow > 2000 gal/day)	1577.6 lb/yr
Other unspecified point and nonpoint sources	8584.4 lb/yr
Total Phosphorus	10,162 lb/yr

Municipal and domestic wastewater treatment facilities with discharges exceeding 2,000 gallons per day that were permitted prior to the July 30, 1984, regulations are not to exceed a daily maximum discharge of 0.5 mg/L total phosphorus. Site approvals and permits for facilities that began discharging after the July 30,

1984, regulations are based on a total phosphorus effluent quality of 0.2 mg/L (30-day average) and the design capacity of the treatment plant. These new allocations may be used only if they are offset by discharge credits for nonpoint source controls.

Point source dischargers that control nonpoint sources of phosphorus are eligible to receive a credit toward their point source phosphorus allocation. One pound of credit will be received for every 2 pounds of phosphorus controlled. The credit will be granted only for nonpoint sources of phosphorus already in existence.

Implications

In 1990, the state conducted a 10-year retrospective conference to examine past successes and failures and to establish some goals for the next 10 years. It was decided that the water quality model used for the Dillon Reservoir worked well and produced accurate projections. It was determined that predictive modeling was unnecessary if the status quo could be maintained. However, refinement of the model and the water quality monitoring effort is expected to continue.

References

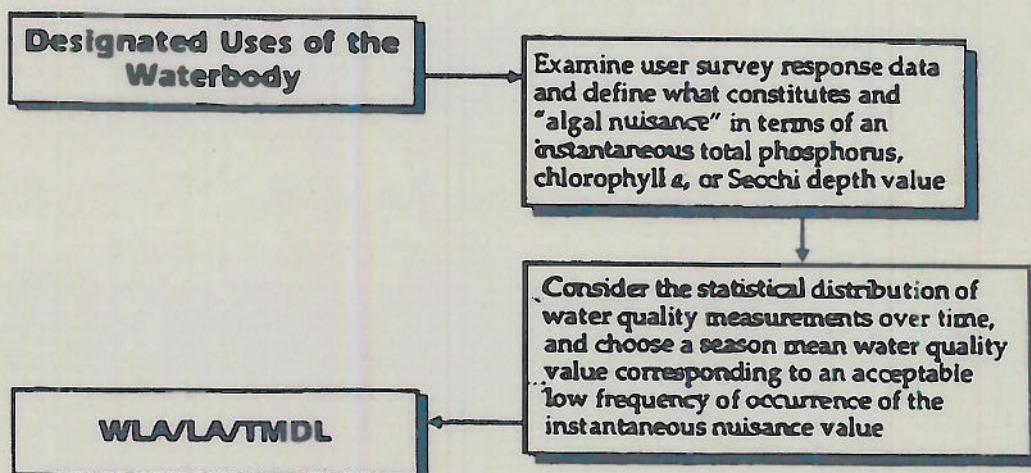
- Carlson, R.E. 1977. A trophic state index for lakes. *Limnol. Oceanogr.* 22:361-368.
- Dillon, P.J., and F.H. Riegler. 1974. The phosphorus-chlorophyll relationship in lakes. *Limnol. Oceanogr.* 19:767-773.
- Lewis, W.M., Jr., J.F. Saunders, D.W. Crumpacker, Sr., and C. Bredecke. 1984. *Eutrophication and land use: Lake Dillon, Colorado*. 202 pp. Springer-Verlag, New York, NY.
- Vollenweider, R.A., 1969. Possibilities and limits of the elementary models concerning the budget of substances in lakes. *Arch. Hydrobiol.* 66:1-36.



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Components	Values for Minnesota
Waterbody Type	lakes
Ecoregion	northern lakes and forests, north central hardwood forests, western corn belt plains, northern glaciated plains
Waterbody's Designated Use	drinking water supply, coldwater fishery, primary contact recreation and aesthetics
Size of Waterbody	not designated
Retention Time	not designated
Chlorophyll <i>a</i> Target	
Nutrient Standard	<p>Total Phosphorus</p> <p>Northern lakes/forests:</p> <p>drinking water supply < 15 µg/L</p> <p>coldwater fishery < 15 µg/L</p> <p>primary contact < 30 µg/L</p> <p>North Central Hardwood Forests:</p> <p>drinking water supply < 30 µg/L</p> <p>primary contact < 40 µg/L</p> <p>Western Corn Belt Plains:</p> <p>drinking water supply < 40 µg/L</p> <p>primary contact < 40 µg/L (full support)</p> <p>< 90 µg/L (partial support)</p> <p>Northern Glaciated Plains:</p> <p>primary contact < 90 µg/L (partial support)</p>
Basis for Standards	subjective user survey data based upon physical appearance and recreational suitability and water quality data for phosphorus, chlorophyll <i>a</i> , and Secchi depth
Water Yield for Watershed	not designated
Annual Load	not designated
Model/Analysis	
Effluent Limitations	not designated

Methodology Used to Derive the Criteria



Minnesota has derived phosphorus criteria for lakes based on relating user-perceived "nuisance algal levels" and recreational impairment to measured water quality parameters, such as phosphorus, chlorophyll *a*, and Secchi depth. This methodology relates lake conditions in terms of the frequencies or "risks," of nuisance algal levels to lake phosphorus levels (Heiskary and Walker, 1988). This provides a method for selecting lake- or regional-specific criteria that will maintain the aesthetic qualities and recreational uses most desired by the people using the lake.

This methodology requires the evaluation of two types of responses: lake responses and user responses. Lake responses involve the statistical analysis of the relationships between phosphorus concentrations and nuisance level frequencies, and decreased transparency of the water column. User responses involve the statistical analysis of the relationship between water quality measurements and user-perceived impairment in physical appearance or recreational potential.

The risk analysis approach describes the lake condition based on the frequency of extreme chlorophyll *a* conditions (i.e., algal blooms) rather than average conditions because user-perceived impairments have been found to be episodic, not continuous; bloom frequencies reflect temporal variability; and blooms are better indicators of potential use impairment (Heiskary and Walker, 1988). Rather than developing criteria by performing linear regressions relating chlorophyll *a* and phosphorus concentrations, Heiskary and Walker (1988) have employed a simple, nonparametric method involving the following steps:

- 1) Arrange the data into paired phosphorus and chlorophyll *a* measurements and divide the data set into 10 intervals based on increasing phosphorus concentrations (discard the remaining observations);

- 2) Within each phosphorus interval, calculate the frequency of chlorophyll *a* class (i.e., the percent of samples exceeding 5, 10, 20, 30, 40, and 60 µg/L);
- 3) Plot the frequency of each chlorophyll *a* class against the median phosphorus concentration in each phosphorus interval;
- 4) Repeat this procedure using phosphorus and transparency pairs.

Extreme value frequencies of chlorophyll *a* and transparency exhibit nonlinear responses to increasing phosphorus concentrations. Frequencies typically reach a phosphorus concentration or "threshold" where they increase dramatically until they reach a point where they level off. The "threshold" indicates the onset of detectable nuisance frequencies and is a logical starting point for criteria development.

The chlorophyll *a* and transparency levels that are perceived as nuisance conditions or use impairments vary regionally, and what may be considered as an acceptable condition in one area may indeed be unacceptable in another locale. User surveys are a useful tool for calibrating user responses to what is considered acceptable in a specific region. The user survey has two response categories: one for the physical appearance and one recreational potential. Each category has five possible ratings that the users may use to best reflect their impressions of the lake (Table 1). The survey should be conducted concurrent with water quality sampling.

Table 1. Lake User (Observer) Survey

A. Please circle the one number that best describes the physical condition of the lake water today:	B. Please circle the one number that best describes your opinion on how suitable the lake water is for recreation and aesthetic enjoyment today:
<ol style="list-style-type: none"> 1. Crystal clear water. 2. Not quite crystal clear, a little algae present/visible. 3. Definite algal green, yellow, or brown color apparent. 4. High algal levels with limited clarity and/or mild odor apparent. 5. Severely high algal levels with one or more of the following: massive floating scums on lake or washed up on shore, strong foul odor, or fish kill. 	<ol style="list-style-type: none"> 1. Beautiful, could not be nicer. 2. Very minor aesthetic problems: excellent for swimming, boating, enjoyment. 3. Swimming and aesthetic enjoyment slightly impaired because of algal levels. 4. Desire to swim and level of enjoyment of the lake substantially reduced because of algal levels (would not swim, but boating is okay). 5. Swimming and aesthetic enjoyment of the lake nearly impossible because of algal levels.

Source: Garrison and Smeltzer, personal communication. Cited in Heiskary and Walker (1988).

Results

The Minnesota Pollution Control Agency (MPCA) collected user survey and water quality data from 40 lakes. Interquartile ranges of measurements within each category (physical appearance, recreational potential) and rating (1-5) were plotted for each water quality parameter. For each water quality parameter, there were distinct differences or gaps between the ranges for "definite algae" and "high algae." "Impaired swimming" was consistent with chlorophyll *a* and phosphorus exceeding 20 µg/L and 40 µg/L, respectively, and Secchi depths of less than 1 m. "No swimming" coincided with chlorophyll *a* and phosphorus concentrations exceeding 40 µg/L and 60 µg/L, respectively, and Secchi depths of less than 1 m (Heiskary and Walker, 1988).

Heiskary and Walker (1988) also performed the risk analysis approach for non-parametric data described above for estimating the frequency of occurrence of a nuisance rating as a function of chlorophyll *a*, phosphorus, and Secchi depth. Data that were collected by the MPCA Citizen Lake Monitoring Program in northern and southern Minnesota were analyzed for the relationship between Secchi depth and recreational suitability. Swimming impairment began at Secchi transparencies of less than 3 m in the north and less than 1 m in the south. In the north, "no swimming" usually began at transparencies of less than 2 m, but less than 0.5 m in the south. Citizens from the middle of the state typically chose transparencies midway between these extremes. Transparencies less than 0.5 m were considered "no swimming" regardless of regional location, and transparencies between 0.5 to 1 m were either "swimming impaired" or "no swimming." These varying responses exemplify the fact that recreational suitability is indeed a region-specific parameter.

Implications

This type of data has been used by Minnesota as the basis for developing site-specific criteria for chlorophyll *a*, phosphorus, and transparency for lakes. This is done by determining the nuisance criteria: extreme chlorophyll *a* concentration (e.g., > 30 µg/L), reduced transparency (e.g., < 1 m), recreational potential rating (e.g., "impaired swimming"), and physical appearance rating (e.g., "high algae") (Heiskary and Walker, 1988). In addition, an acceptable risk level, or probability, that nuisance conditions will occur (e.g., 1, 5, 10 percent, etc.) must be established. Minnesota has developed criteria by determining the phosphorus concentrations that coincide with each nuisance frequency and setting limits that are acceptable for each region.

The regional diversity of Minnesota's lakes and watershed made the development of a single statewide criterion impractical. The methodology described above has been used on a lake- and ecoregion-specific basis and is useful for discerning relationships other than phosphorus concentration and perceived impairment in aesthetics or recreation potential. Phosphorus concentrations can be linked to hypolimnetic oxygen depletion, specific lake uses, and regional patterns in lake phosphorus concentration. This procedure for criteria development considers phosphorus impacts on lake condition (as measured by chlorophyll *a*, bloom frequency, transparency, and hypolimnetic oxygen depletion); impact on lake users (aesthetics, recreation, fisheries, water supply, etc.); and attainability (as related to watershed characteristics, regional phosphorus export values, lake morphometry, etc.). In addition, the method quantifies the "fishable-swimmable" goals of the Clean Water Act and expresses lake conditions in terms that are more easily understood by the public.

References

- Garrison, V., and E. Smeltzer. 1987. Personal communication (to S.A. Heiskary). Environmental Engineer, Vermont Department of Water Resources, Montpelier, VA.
- Heiskary, S.A., and W.W. Walker. 1988. Developing phosphorus criteria for Minnesota lakes. *Lake and Res. Manage.* 4(1):1-9.
- NALMS. 1992. Developing eutrophication standards for lakes and reservoirs. Prepared by the Lake Standards Subcommittee, North American Lake Management Society, Alachua, FL.

North Carolina

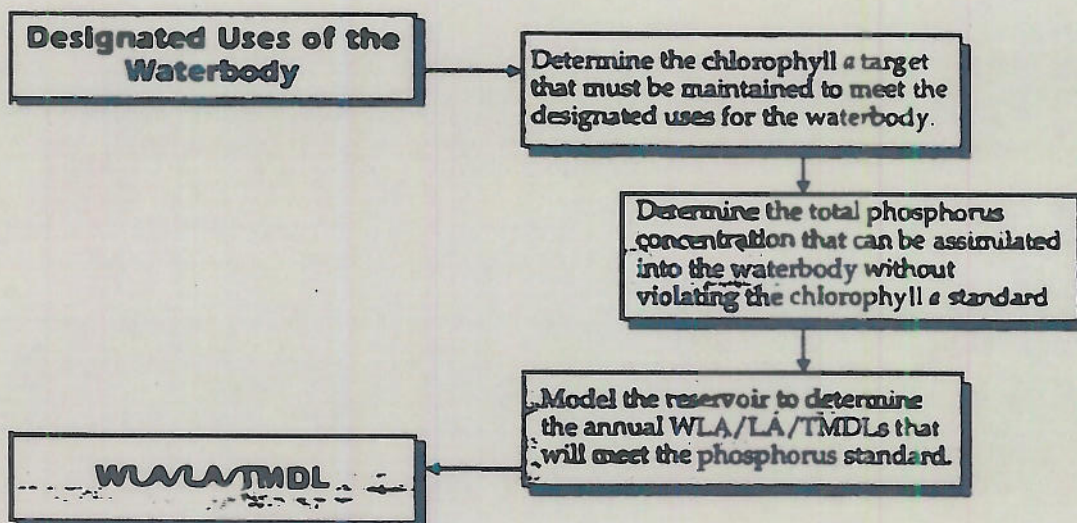
The following summary table contains a checklist of the key components required for developing ecoregion- and waterbody type-specific water quality criteria. The values listed below are those used for the lakes, streams, and estuaries in the State of North Carolina.

Components	Values for North Carolina
Waterbody Type	lakes, streams, and rivers
Ecoregion	Mountain, piedmont, and coastal plain
Waterbody's Designated Use	not designated
Size of Waterbody	not designated
Retention Time	not designated
Chlorophyll <i>a</i> Standard	40 µg/L
Nutrient Standards	<p>Instream Standards (proposed)</p> <p>Piedmont and Coastal Lakes (including coves): 50 µg/L TP</p> <p>Mountain Lakes (including coves): 20 µg/L</p> <p>Streams and Rivers: insufficient data for criteria development</p> <p>Estuaries: 50 µg/L TP</p> <p>500 - 750 µg/L TN</p> <p>Upper estuaries and slower-moving tributaries should be addressed on a case-by-case basis.</p> <p>Narrative Standard (proposed)</p> <p>"Nutrients: Substances which stimulate aquatic plant growth shall not be present in concentrations sufficient to result in growths of microscopic or macroscopic aquatic vegetation such that the standards established pursuant to the Rule would be violated or the intended best usage of the waters or the water quality necessary to maintain these uses would be impaired. Total nitrogen concentration shall be limited where necessary to maintain biological integrity as defined by 15A NCAC 2B.0202."</p>

Components	Values for North Carolina
Basis for Standards	Hydrologic and water quality data from 1982 to 1991
Water Yield for Watershed	not designated
Annual Load	not designated
Model/Analysis	Linear regression analyses using observed and predicted values for chlorophyll <i>a</i> and total phosphorus
Effluent Limitations	not designated

Methodology Used to Derive the Criteria

The methodology used by the North Carolina Department of Environment, Health, and Natural Resources to develop ecoregion- and waterbody-specific total nitrogen (TN) and total phosphorus (TP) criteria is outlined below..



Lakes

North Carolina collected ambient lake data for chlorophyll *a*, TP, TN, and total organic nitrogen (TON) from 1983 to 1990 for 132 lakes located throughout the state. Lakes suffering from heavy algal blooms or excessive macrophyte growth, as well as blackwater or muddy lakes, were excluded from the analyses because these factors also influence primary productivity. Mean summer (May through September) concentrations were calculated because they represent the growing season. Because these values are not normally distributed, log transformations had to be performed to allow the use of parametric statistical analyses.

Linear regressions were performed on the data to determine (1) the correlation between chlorophyll *a* and each nutrient, and (2) the nutrient concentrations that coincided with the chlorophyll *a* standard of 40 µg/L.

There were no correlations between the various nitrogen species and chlorophyll *a*. This could be expected because these lakes are known to be limited by phosphorus, not nitrogen. There was a significant correlation, however, between TP and chlorophyll *a*. Regression analyses of TP versus chlorophyll *a* predict a mean summer TP concentration of 100 µg/L to coincide with a mean summer chlorophyll *a* concentration of 38.2 µg/L, and a mean summer TP concentration of 50 µg/L to coincide with a mean summer chlorophyll *a* concentration of 21.7 µg/L. Additional studies in approximately 15 lake arms in North Carolina indicate the frequent occurrence of algal blooms at TP concentrations above 50-100 µg/L. A criterion of 100 µg/L would be insufficient to protect the 40 µg/L chlorophyll *a* standard, and therefore the criterion was set at 50 µg/L.

Many lakes in the state are oligotrophic and have ambient TP concentrations lower than 50 µg/L. The TP concentrations of these lakes, as well as Secchi transparency, chlorophyll *a*, and TN, were analyzed. The TP concentration for 89 percent of these lakes was 20 µg/L, and the mean for all of the oligotrophic lakes was 15 µg/L. Mean TP concentrations for the mesotrophic and eutrophic lakes in the state were 26 µg/L and 59 µg/L, respectively. These results supported the use of a TP criterion of 20 µg/L for oligotrophic lakes.

Streams and Rivers

Historically, chlorophyll *a* has been collected in streams and rivers for only special studies. For this reason, nutrient levels were measured in streams rated as unimpacted or excellent to determine background concentrations. To determine

the distribution of the bulk of the values, data in the 25th and the 75th quartiles were analyzed. Fifty-nine percent of the stations had TP concentrations between 50 and 100 $\mu\text{g/L}$, and 73 percent had TN concentrations between 500 to 1000 $\mu\text{g/L}$. The stream that served as the control for a separate 2-year study had TN and TP concentrations below 50 $\mu\text{g/L}$ and 500 $\mu\text{g/L}$, respectively, and only once during the 2-year study did the chlorophyll *a* concentration exceed the standard of 40 $\mu\text{g/L}$.

Estuaries

Data collected from the Neuse and Chowan estuaries indicate that winter nutrient concentrations and flow play a more significant role in summer algal blooms than do summer nutrient concentrations. Data analyses compared mean winter chlorophyll *a* concentrations to mean summer chlorophyll *a* concentrations and mean summer nutrient concentrations. The only significant correlations noted were between mean winter TON in the Neuse estuary and mean summer chlorophyll *a* concentrations. This finding is consistent with the belief that nitrogen is the limiting factor with regard to algal growth in estuarine ecosystems.

Mean summer and winter values of TP and TN collected from 1980 through 1990 from six estuarine basins were approximately 100 $\mu\text{g/L}$ and 1000 $\mu\text{g/L}$, respectively. Mean chlorophyll *a* concentrations were below the 40 $\mu\text{g/L}$ standard; however, there were excursions of the standard during each season. Data collected from the Pamlico and Neuse estuaries during the summer of 1988, however, showed that TN concentrations that exceeded the 500-599 $\mu\text{g/L}$ range resulted in mean chlorophyll *a* concentrations that exceeded 40 $\mu\text{g/L}$, indicating that a criterion of 1000 $\mu\text{g/L}$ is not sufficiently protective.

Results

Lakes

The data indicate that a TP criterion of 50 $\mu\text{g/L}$ would be protective of the chlorophyll *a* standard and would prevent undesirable water quality conditions in the majority of North Carolina's piedmont and coastal lakes.

Most of the oligotrophic lakes in North Carolina are located in the mountains and already meet the 20 µg/L criterion. Lakes that do not meet the criterion have a history of degradation and are listed as threatened or impaired. Some piedmont and coastal lakes meet the oligotrophic or mountain criterion for TP. These lakes may be recommended for classified as high quality waters (HQW) or outstanding resource waters (ORW) if use attainability analyses support the recommendation.

Streams and Rivers

Chlorophyll *a* concentrations have not been routinely sampled in the state's free-flowing waters. However, the data on the background concentrations of TN and TP support the use of 50 µg/L TP and 500 µg/L TN as appropriate criteria where streams meet lakes and reservoirs. Currently, however, North Carolina has not adopted or implemented nutrient criteria for streams and rivers.

Estuaries

The results from the estuarine research were too variable to develop conclusive nutrient criteria for estuaries. Research has shown that TN-to-TP ratios of 11-15:1 will provide the proper balance to prevent the growth of nuisance blue-green algae. Therefore, until further research is conducted, nutrient limits for estuaries have been established at 50 µg/L for TP and 550 to 750 µg/L for TN.

Implications

The task of developing criteria for free-flowing waters is complicated by the process of continuous nutrient recycling or nutrient swirling, the continuous flow of water, and the undetermined losses of phytoplankton resulting from grazing by zooplankton. In addition, routine sampling for chlorophyll *a* should be conducted in the free-flowing waters to provide a database sufficient to provide the information useful for rigorous statistical analyses.

More knowledge of estuarine nutrient assimilation capacities and recycling characteristics need to be acquired because it is unlikely that nutrient loadings and concentrations by themselves will be useful in predicting the potential for algal

blooms. Estuaries are highly variable systems, and more information concerning the role of flow, flushing, vertical stratification, irradiance, and salinity regimes must be known to fully understand the susceptibility of estuarine and riverine regions to algal blooms (Paerl, 1987). Nutrient criteria alone may not be sufficient to protect these ecosystems from harmful algal blooms.

Paerl, H.W. 1987. Dynamics of blue-green algal (*Microcystis aeruginosa*) blooms in the lower Neuse River, North Carolina: Causative factors and potential controls. Report #229. Water Resources Research Institute, University of North Carolina.

Region 4

The following summary table contains a list of the key components that have been used by Region 4 for impoundments located in the southeast Piedmont.

Components	Values for Region 4
Waterbody Type	monomictic impoundments (man-made lakes with an area greater than 10 acres that were formed for conservation, water supply, flood control, recreation, hydro-power, and irrigation purposes). Monomictic means these impoundments undergo one annual thermal turnover in the autumn.
Ecoregion	southeastern piedmont.
Waterbody's Designated Use	drinking water supply, primary contact recreation and aesthetics
Size of Waterbody	area greater than 10 acres
Retention Time	not designated
Chlorophyll <i>a</i> Guideline	$\leq 15\mu\text{g/l}$; recommended for water supply impoundments $\geq 25\mu\text{g/l}$; recommended to maintain minimal aesthetic environment for viewing pleasure, safe swimming, and good fishing and boating
Other water quality guidelines	clarity: ≥ 1.5 m (support) ≤ 1.0 m (non-support)
Basis for Guidelines	water samples of chlorophyll <i>a</i> , total phosphorus (TP), bioavailable phosphorus (BP), total nitrogen (TN), total suspended solids (TSS), limiting nutrient, alkalinity, Secchi depth, and flow (at stream sites entering impoundments)
Water Yield for Watershed	not designated
Annual Load	not designated
Model/Analysis	risk analysis approach; and the predictive model, CNET-Reservoir Eutrophication Modeling Worksheet Version 1.0
Effluent Limitations	not designated

Methodology Used to Derive the Criteria

Water quality data were collected from April to October in 1989 and 1991 on a weekly and biweekly basis in 17 small monomictic impoundments located in the southeastern Piedmont region. The water quality parameters that were sampled include chlorophyll *a*, total phosphorus (TP), bioavailable phosphorus (BP), total nitrogen (TN), total suspended solids (TSS), limiting nutrient, alkalinity, Secchi depth, and flow (at stream sites entering impoundments). The impoundments are used for conservation, water supply, flood control, recreation, hydro-power, and irrigation purposes. The sampling period coincided with the maximum recreational and water supply uses, as well as the period of maximum growth of aquatic plants.

The methodology used to derive limits to control eutrophication enlisted expert opinion, information found in the literature, and water quality data collected from the impoundments. Emphasis was placed on using actual data in a risk, or probability, analysis approach to address eutrophication problems encountered in southeastern impoundments. This approach expresses impairment in terms of the frequency of occurrence of extreme chlorophyll *a* conditions. This is accomplished by dividing the growing season means for each site into intervals, computing the frequency of each class (i.e., percent of values $\geq 20\mu\text{g/l}$), and plotting the frequency of each class versus the mean seasonal value for the parameter being evaluated (e.g., total phosphorus, chlorophyll *a*, transparency). This method was used to determine criteria for chlorophyll *a* and SD because it allows decisions to be based on any particular mean value, rather than on a seasonal or yearly mean or maximum.

Chlorophyll *a*

Chlorophyll *a*, a commonly-used indicator of eutrophication, was chosen because it is a useful measure for estimating phytoplankton blooms (chlorophyll *a* $\geq 15\mu\text{g/L}$) and the water quality problems associated with excessive algae. Region 4 observed that the percent of occurrence of bloom frequencies (i.e., $\geq 15\mu\text{g chlorophyll } a/\text{L}$) decreases as bloom frequency increases (Raschke, 1993). A graph of the percent of bloom occurrence (i.e., $\geq 15\mu\text{g chlorophyll } a/\text{L}$) versus mean chlorophyll *a* concentrations show an obvious leveling of the curve at $30\mu\text{g chlorophyll } a/\text{L}$, after which the curve converges toward the 100 percent ordinate. Straight line equations were derived for each exceedance class within the $10\text{-}30\mu\text{g chlorophyll } a/\text{L}$ limit.

$$\% \geq 15 \pm 0.43 = 2.88 (X) - 12.92$$

$$\% \geq 20 \pm 0.36 = 2.77 (X) - 25.58$$

$$\% \geq 25 \pm 0.54 = 2.31 (X) - 24.46$$

$$\% \geq 30 \pm 0.43 = 1.90 (X) - 21.26$$

$$\% \geq 40 \pm 0.15 = 1.18 (X) - 14.16$$

where: X = mean season-corrected chlorophyll *a* concentration

These curves indicate that at a growing season average chlorophyll *a* concentration of 15 µg/L, 30 percent of the time the chlorophyll *a* concentration would exceed 15 µg/L and 7 percent of the time it would exceed 30 µg/L.

From experience, the authors noted the following observations: there is no discoloration of the water and no problems when chlorophyll *a* concentrations range from 0 to 10 µg/L; some discoloration and algal scums are present with chlorophyll *a* ranging from 10 - 15 µg/L; chlorophyll *a* concentrations ranging from 20 - 30 µg/L cause deep discoloration of the water, frequent scums, and matting of algae. When chlorophyll *a* concentrations exceed 30 µg/L, the discoloration is more intense and algal mats occur more frequently. Based on experience, results from this study, and observations by other researchers (Carlson, 1977; Lillie and Mason, 1983; Walmsey, 1984; Burden et al., 1985; Heiskary and Walker, 1988), it was decided that a growing season mean chlorophyll *a* concentration of ≤ 15 µg/L corrected chlorophyll *a* should be used as the criterion for impoundments that are used for drinking supplies. Additionally, this limit will allow the impoundments to meet all other designated uses.

With an average growing season chlorophyll *a* concentration of 25 µg/L, one could expect that chlorophyll *a* concentrations would be ≥ 30 µg/L 26 percent of the time and that 59.1 percent of the time the algal growth would be sufficient to discolor the water and form scums. Algal bloom reports from North Carolina indicated a greater frequency of fish kills when chlorophyll *a* concentrations exceeded 25 µg/L; therefore the upper limit for minimizing water quality problems, while maintaining an aesthetically acceptable environment, was set at 25 µg/L.

Secchi Depth Transparency:

The risk assessment, or probability of exceedance, approach was used to derive acceptable Secchi disc transparencies for 19 impoundments. A growing season mean depth of 1 meter coincides with Secchi depths of ≤ 0.5 m, ≤ 1.0 m, and ≤ 2.0 m for 13, 72, and 100 percent of the time, respectively. In addition, the Carlson Trophic State Index for a 1-meter Secchi depth considers the waterbody to be eutrophic to hypereutrophic, and unsafe swimming conditions would occur 72 percent of the time. Also, studies have indicated that a fish survival and production are adversely affected by the low dissolved oxygen and muddy waters having a transparency of 1-meter or less (Boyd, 1979, 1990).

Non-algal Secchi depth transparencies were calculated using two methods. The first method derives the value from the measured transparency value (Rachle, 1993):

$$SD_o = 1/SD_m - bC$$

where:

SD_o = transparency depth of impoundment at zero chlorophyll *a*

SD_m = mean Secchi depth in meters

b = chlorophyll *a*/Secchi slope (m^2/mg) = 0.025

C = mean corrected chlorophyll *a* concentration ($\mu g/l$)

A Secchi depth transparency of 1.07 meters (SD_m) in an impoundment having a chlorophyll *a* concentration of 1.11 $\mu g/L$ (C) and a chlorophyll *a*/Secchi slope of 0.025, is equivalent to a chlorophyll *a* free transparency of 1.11 meters (SD_o).

The second method used the mean TSS stream loading and the mean TSS impoundment loading to calculate the non-algal Secchi depth transparency for the impoundment. The equations are shown below:

$$TSS_i = 0.0011 (TSS_s) + 6.40$$

$$SD_i = 31.44 (TSS_i)^{-1.31}$$

Where: TSS_i = X non-algal impoundment TSS in mg/l

TSS_s = X stream TSS in $lb/ft\text{-}day$

SD_i = X impoundment non-algal influenced SD in meters

ft = X impoundment depth in feet

An upper limit of ≥ 1.5 meters Secchi depth transparency was considered to be a reasonable limit for impoundments located in the southeastern piedmont region for the following reasons: (1) the National Academy of Sciences (NAS, 1973) determined that at Secchi depths of ≥ 1.5 m, unsafe swimming conditions would occur 35-40 percent of the time; (2) low dissolved oxygen levels at the 1.5-meter limit only minimally affect fish survival; and (3) it is highly unlikely that this limit would allow for nuisance weed coverage (> 40 percent) (Raschke, 1993).

Results

Chlorophyll *a*

The mean growing season chlorophyll *a* guideline for water supply impoundments is $\leq 15 \mu g/L$. This limit is expected to result in few nuisance algal blooms or scums and, therefore, limited clogging of water supply filters and few taste and odor problems. To maintain minimal aesthetic environment for viewing, safe swimming, and good fishing and boating, a limit of $\geq 25 \mu g/L$ has been established.

Secchi Depth Transparency:

A mean growing season Secchi disc transparency of ≥ 1.5 meters was established for water supply impoundments. This guidelines should prevent the clogging of water supply filters, produce only a low risk of fish kills from low oxygen, maintain normal fish production, and provide safe swimming conditions 60 to 65 percent of the time. Mean growing season Secchi disc transparencies of > 1 meter are considered acceptable for fishing and some swimming in non-water supply impoundments. Mean growing season transparencies less than 1 meter are aesthetically undesirable, restrict swimming opportunities, and significantly increase the risk of fish kills and decrease fish production.

Implications

Impoundments in the piedmont watersheds are subject to relatively high sediment loadings and intensive fertilization and were found to be phosphorus limited or phosphorus/nitrogen co-limited. Some of the impoundments are subject to internal phosphorus loading (i.e., the release of phosphorus from the sediments), which has the effect of maintaining a relatively high trophic condition (mesotrophic or eutrophic)(Raschke, 1993). In fact, two of the impoundments that were studied had total internal phosphorus loadings contributing 53 percent and 68 percent of the total phosphorus loading.

Loadings models can be used to predict nuisance algal blooms based on phosphorus loads, internal impoundment phosphorus concentration, and phytoplankton response (Raschke, 1993). Region 4 used a simplified phosphorus-limited version of the U.S. Army Corps of Engineers BATHTUB model (Walker, 1986) known as CNET.WK1. The model is a Lotus 1-2-3 spreadsheet that performs a steady-state water and nutrient balance, accounting for advective and diffusive transport and nutrient sedimentation, and predicting eutrophication and associated water quality problems in impoundments.

Maximum mean stream concentrations of total phosphorus (i.e., internal impoundment load plus the surface load) were used to calculate observed versus predicted mean corrected chlorophyll *a* values of 54 percent. The error was reduced to 34 percent when the comparison was done using the observed median concentrations versus the predicted median concentrations. Using the same set of data, the model compared observed Secchi transparencies to predicted transparencies and it calculated errors ranging from -35 to 14 percent.

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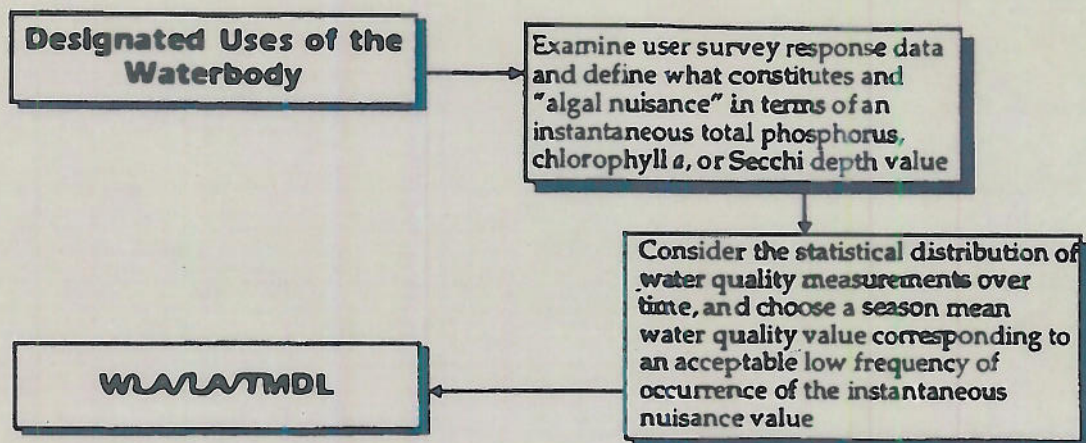
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Lake Champlain, Vermont

The following summary table contains some of the key components that were used for developing numeric water quality criteria from user survey data for Lake Champlain, Vermont.

Components	Values for Lake Champlain, Vermont
Waterbody type	lake
Ecoregion	not given
Waterbody's Designated Use	not given
Size of Waterbody	not given
Retention Time	not given
Chlorophyll <i>a</i> Target	approximately 0.003 mg/L (extrapolated from graph)
Nutrient Standard	0.014 mg/L total phosphorus (in-lake summer mean)
Basis for Standards	Five years (1987-1991) of user survey data that have been collected by the Vermont Lay Monitoring Program; the water quality parameters for which there are data (900 individual observations) are total phosphorus, chlorophyll <i>a</i> , Secchi disk transparency, and user perceptions of nuisance algae levels and recreational impairment.
Water Yield for Watershed	not given
Annual Load	not given
Model/Analysis	Walker's 1985 algorithm for calculating nuisance frequencies from season mean water quality values. VTDEC used the low (1%) frequency of occurrence of the "moderate" nuisance level.
Effluent Limitations	not given

Methodology Used to Derive the Criteria



The Vermont Lay Monitoring Program is a citizen volunteer monitoring effort that has conducted long-term water quality monitoring on Lake Champlain. Since 1987, the monitoring effort has included a user survey form that is completed each time water quality parameters (total phosphorus, chlorophyll *a*, and Secchi disk transparency) are sampled. The user survey forms requested responses to two questions, marked A and B, which pertained to the observed levels of nuisance algae and impairment to recreational uses. The four responses for each item are listed below:

Question A

crystal clear
a little algae
definite algal greenness
high algae levels

Question B

beautiful
very minor problems
use slightly impaired
enjoyment substantially reduced

From the survey results, a rating of the physical suitability for recreation and enjoyment is produced. The frequency distribution of responses to the levels of impairment, as observed by the volunteer, are plotted versus the measured phosphorus, chlorophyll, and transparency levels. The transparency levels of the water are high when total phosphorus and chlorophyll *a* levels are low, and the transparency levels are low when phosphorus and chlorophyll levels are high.

This method provides a way to quantify an observer's evaluation of the level of recreational impairment to instantaneous levels of phosphorus, chlorophyll, and transparency.

The development of a numeric in-lake water quality criterion using user survey data involves a two-step process. First, the user survey data must be examined to determine what instantaneous total phosphorus, chlorophyll *a*, or Secchi depth values constitute an "algal nuisance." In addition, lake eutrophication water quality standards are better described by season mean values than by instantaneous values. Therefore, it is necessary to determine the statistical distribution of the water quality measurements over time and then choose a season mean water quality value that corresponds to an acceptably low frequency of occurrence of the instantaneous nuisance value.

A procedure developed by Walker (1985) for deriving season mean water quality criteria from sampling frequency distribution parameters provides an estimate of the frequency with which an instantaneous nuisance water quality value will be exceeded during a particular season, as a function of the variable's mean value.

The algorithm developed by Walker (1985) to derive the frequency of exceedance is shown below:

$$\begin{aligned} ML &= \ln(MA) - 0.5 SL^2 \\ SL^2 &= \ln(1 + (SA/MA)^2) \\ Z &= (\ln C - ML)/SL \\ V &= \exp(-Z^2/2)/2.507 \\ W &= 1/(1 + 0.33267|Z|) \\ X &= V(0.4361684W - 0.1201676W^2 + 0.937298W^3) \\ P &= X \text{ if } Z > 0 \\ P &= 1 - X \text{ if } Z \leq 0 \end{aligned}$$

where:

- MA = arithmetic mean water quality value
- SA = arithmetic standard deviation, calculated from the regression equations given below
- Z = value for the standard normal deviate
- C = instantaneous nuisance water quality criterion
- V, W, X = variables used in calculating the cumulative normal distribution function
- P = probability of exceeding C

The relationship between the within-season arithmetic mean (MA) and the arithmetic standard deviation (SA) for each water quality variable is established using regression analyses. The Vermont Department of Environmental Conservation

used the entire 1977-1991 Lake Champlain eutrophication monitoring database in deriving the following regression equations:

Lake Champlain regression equations:

Total Phosphorus ($\mu\text{g/l}$):

$$\log_{10} \text{SA} = -0.585 + 1.006 \log_{10} \text{MA} \quad (R^2 = 0.56)$$

Chlorophyll a ($\mu\text{g/l}$):

$$\log_{10} \text{SA} = -0.507 + 1.296 \log_{10} \text{MA} \quad (R^2 = 0.76)$$

Secchi Depth (m):

$$\log_{10} \text{SA} = -0.571 + 0.724 \log_{10} \text{MA} \quad (R^2 = 0.58)$$

The instantaneous nuisance criteria were used with Walker's algorithm to define the relationships between nuisance frequencies and mean water quality values. For each water quality variable, there are well-defined critical threshold mean values beyond which the frequency of nuisance conditions increase significantly. The Vermont Department of Environmental Conservation used these critical threshold values to define water quality mean criteria corresponding to a low frequency of nuisance conditions.

Results

The Vermont Department of Environmental Conservation defined three categories (low, moderate, and severe) of nuisance algal conditions for Lake Champlain (Table 1). Based on these definitions, the corresponding instantaneous water quality values could be extrapolated from graphs of the frequency of the nuisance condition versus each water quality parameter (Figure 1).

Graphs of the frequency of response versus total phosphorus (TP) showed that at TP concentrations below 25 $\mu\text{g/l}$, user descriptions were predominantly "a little algae" and "very minor problems". When TP concentrations exceeded 25 to 30 $\mu\text{g/l}$, the more commonly used responses were "definite algal greenness" and "use slightly impaired." In addition, responses such as "high algae levels" and "enjoyment substantially reduced" became more frequent with TP levels above 25 $\mu\text{g/l}$. Using Walker's (1985) algorithm, a summer mean values corresponding to an instantaneous TP concentration of 25 $\mu\text{g/l}$ was calculated. The results that are

Table 1. Definitions of each nuisance level and the corresponding instantaneous water quality values for Lake Champlain

Nuisance Level	Definition	TP (µg/l)	Chla (µg/l)	Secchi (m)
Low	20% of lake users see definite algal greenness or high algae and find their enjoyment of the lake slightly or substantially impaired.	15	2	5
Moderate	50% of lake users see definite algal greenness or high algae and find their enjoyment of the lake slightly or substantially impaired.	25	8	3
Severe	30% of lake users see high or severe algae levels and find their enjoyment of the lake substantially reduced or impossible.	40	20	1

generated from Walker's (1985) algorithm are illustrated in Figure 1.

Based on these findings, the Vermont Water Quality Board established an in-lake summer mean total phosphorus criterion of 14 µg/l for seven major segments of Lake Champlain. The criterion is based on a low (1%) frequency of occurrence of the

"moderate" nuisance level. Other segments of the lake required either higher or lower criteria, depending on the water quality characterization of each particular segment.

Implications

The nutrient management goal for Lake Champlain is to "reduce phosphorus and other nutrient inputs to Lake Champlain so as to promote a healthy and diverse ecosystem and provide for sustainable human use and enjoyment of the lake" (Smeltzer, 1992). The initial goal of the authorities in charge is to "establish uniform interstate and international numeric eutrophication-related water quality standards for each segment of the lake" (Smeltzer, 1992).

In a study conducted by Smeltzer and Heiskary (1990), statistically significant relationships between user survey data and water quality measurements were noted using data obtained from Vermont and Minnesota. Although, the relationship was found to differ greatly from region to region, it was concluded that the methodology would be useful for a variety of lake management applications, including the development of region-specific state water quality standards. The analysis of user survey data presents a quantitative, objective procedure for deriving numeric water quality criteria, while simultaneously moving towards maximizing human use and enjoyment of a waterbody.

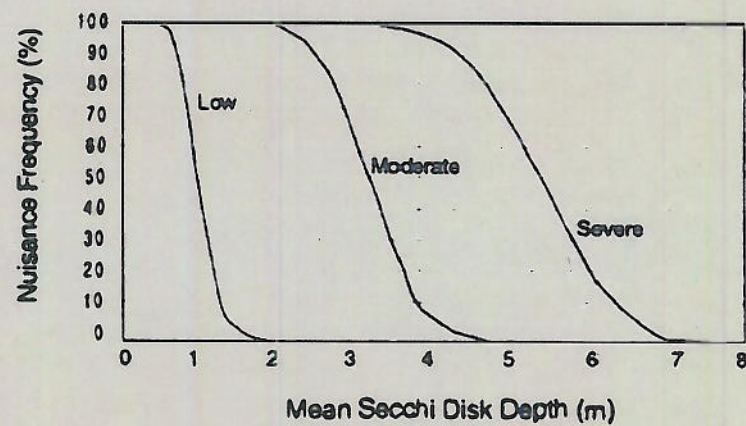
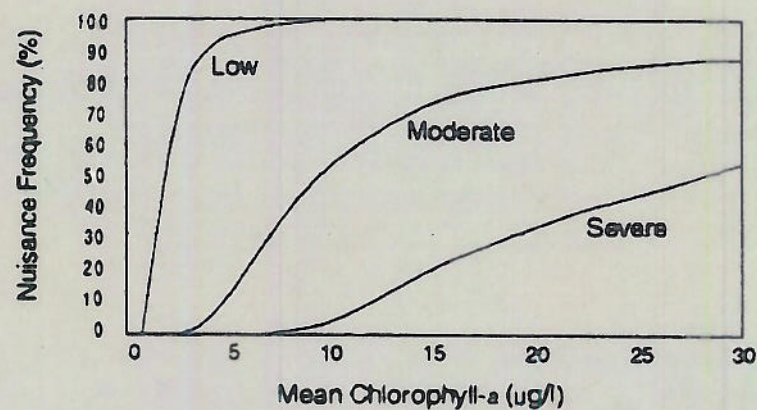
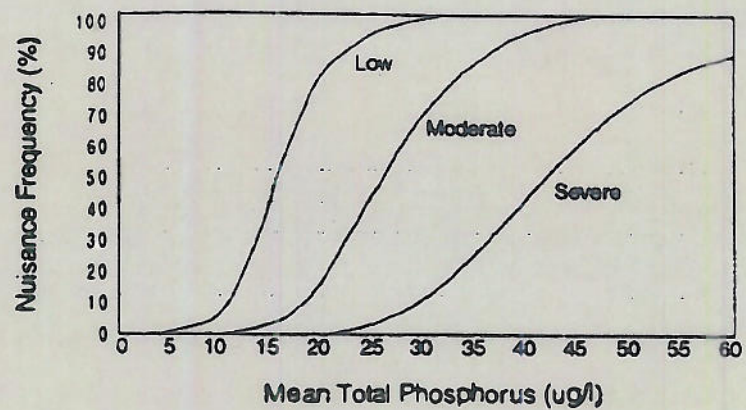


Figure 1. Frequency of low, moderate, and severe nuisance conditions during the summer in Lake Champlain, as a function of mean water quality values. (Source: Smeltzer, 1992)

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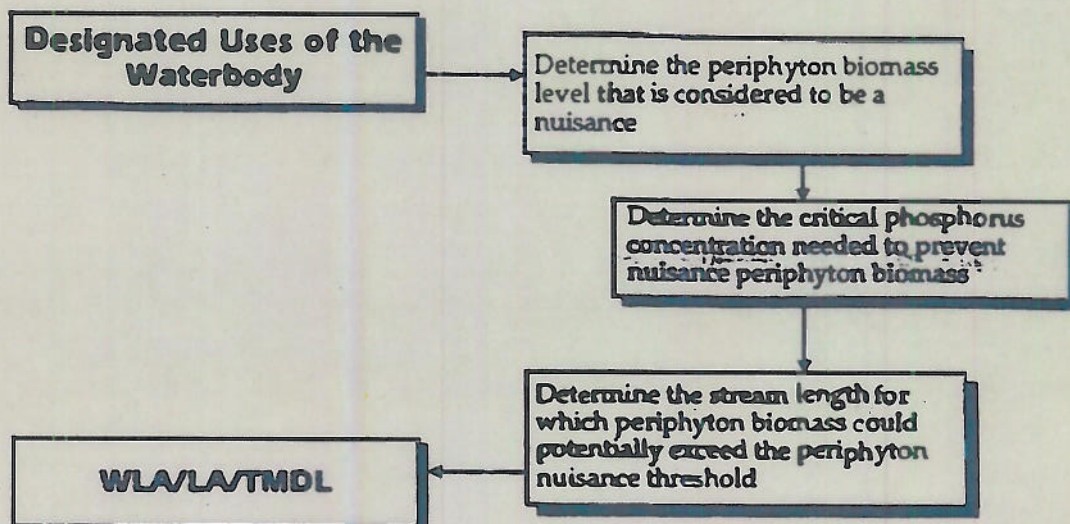
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Spokane River, Washington

The following summary table contains a list of the key components that were used by Welch et al. (1989) to predict nuisance threshold levels of periphyton biomass for the lower Spokane River in the State of Washington.

Components	Values for Cherry Creek Reservoir
Waterbody type	river
Ecoregion	not given
Waterbody's Designated Use	not given
Size of Waterbody	63 m; average stream width 29 km; lower segment of Spokane River
Flow	38 m ³ /s; 20 year low flow
Periphyton biomass nuisance Threshold levels	150 to 200 mg chl <i>a</i> /m ²
Nutrient Standard	not applicable
Basis for Standards	exceedance of nuisance threshold for periphyton biomass
Water Yield for Watershed	not given
Annual Load	not given
Model/ Analysis	growth kinetic accrual model for periphyton biomass
Effluent Limitations	not given

Methodology Used to Derive the Criteria



An approach has been developed for estimating the critical phosphorus concentration to prevent nuisance periphyton biomass. The methodology is based on various factors, including uptake kinetics, that affect periphyton growth. A model that has been calibrated to the growth of filamentous periphyton in artificial channels is applied to the growth of periphyton on natural and artificial substrata in the lower Spokane River. An additional procedure has been developed to estimate, based on the inflow soluble reactive phosphorus (SRP)

A wasteload allocation study was conducted on the Spokane River. Data on periphyton accrual was collected from artificial substrata during July through October, 1980 and 1982 (Gibbons et al., 1984), and from natural substrata during the same months from 1984 to 1986 (Patmont and Pelletier, 1987). Seasonal mean concentrations of ambient SRP were determined for the natural substrata based on weekly observations from July through September. SRP concentrations and velocity data were collected for the artificial substrata during a 2-week time period prior to the periphyton collections. These data were to be used to define management options based on a relationship between phosphorus concentrations and periphyton biomass.

There are differences in the phosphorus concentrations that saturate growth rates and those that maximize accrual rates of thick mats (Bothwell, 1985, 1988) and these differences restrict the use of correlation analyses for predicting the periphyton biomass. To circumvent the conceptual restriction, a growth-kinetic model for steady-state biomass was developed. The model, shown below as Equation 1, was calibrated against the growth of the filamentous green algae, *Mougeotia*, in artificial channels over a range of velocities and SRP concentrations.

Equation 1:

$$B = (B_{\max} - (K_2 V^0) / [K_1 \mu L (K_f + K_{fo})]) \times [1 - e^{-K_1 \mu L (K_f + K_{fo})}] \quad (1)$$

- Where:
- B = periphyton biomass (mg chl *a*/m²)
 - B_{max} = maximum areal periphytic biomass that can be sustained in a mat (560 mg chl *a*/m² in channels)
 - μ = uptake rate of SRP based on Michaelis-Menton kinetics with μ = 0.22e^{1/10} (Eppley, 1972)
 - L = light reduction factor, which was 0.755 using the equation of Steel (1962)
 - V = velocity (cm/s)
 - K_{fo} = non-turbulent mass transfer coefficient = 0.0094 cm/s
 - K_f = turbulent mass transfer coefficient (DV/l)^{0.5} where D = 1.5X10⁻⁵ cm²/s and l = 1 cm
 - t = growth period (days)

K₁, K₂, and θ are empirical constants:

- K₁ = constant at 1.2 at low SRP, but increased at concentrations above about 13 μg/L (25 μg/L inflow) according to 0.022P + 1.59
- K₂ = scour coefficient at 0.3 mg chl *a*/m²
= 0.45

In the artificial channels, controlled velocity ranged from 5 to 75 cm/s, SRP from 2 to 75 μg/L, and temperature from 15 to 20 °C. Loss of periphyton biomass from grazing was unaccounted for and scouring was found to be minimal. In fact, scouring is only a factor when there are abrupt increases in velocity and/or when suspended sediment is increased (Seeley, 1986).

Saturation of filamentous green algae was shown to occur at SRP concentrations of 15 μg/L, therefore, for application to the Spokane River, SRP concentrations were set at a half-saturation concentration of 8 μg/L; light was assumed to be non-limiting in the Spokane River, so L = 1.0; average river velocity was 38 cm/s (± 22); and the mean growing period for artificial substrata was 56 (18-117) days. The effects of uncertainties that were incorporated into the model predictions, such as estimates of river temperature, velocity and accumulation periods, as well as laboratory-derived data (e.g., K₁) were examined using first-order uncertainty analysis methods (Cornell, 1973).

The means of periphyton biomass observed on days 12, 14, and 16 in replicate channels for each of six SRP treatment levels were used to calibrate the model. The resulting six observations for maximum biomass for each SRP concentration. The

95% confidence limit of the observed biomass in the six SRP treatment levels, using velocities of 35 and 45 cm/s, ranged from ± 12.7 to ± 41 percent and averaged ± 27.4 percent, indicating the amount of variability that could be expected even without losses from grazing.

Equation 2 shown below was derived to provide a method for estimating the stream length (D_c) for which periphyton biomass could potentially exceed the nuisance threshold. The potential nuisance biomass level, stream geometry, flow, and the available SRP concentration relative to a critical value are related to a critical distance in the stream. The equation is as follows:

Equation 2:

$$D_c = Qr (SRP_i - SRP_c) / [P / chl\ a - day) B_n TW 10^3\ m / km] \quad (2)$$

- Where: SRP_c = concentration (mg/m^3) producing the threshold nuisance biomass ($150-200\ mg\ chl\ a/m^2$) in the growth period
- SRP_i = influent concentration (ambient river and groundwater, mg/m^3) to the stream segment
- Q = daily flow in m^3/day (20 year low flow is $38\ m^3/s$)
- r = accounts for the recycle rate (unitless; 1.5 after Newbold et al., 1982)
- $P/chl\ a$ = average uptake rate by the periphyton mat/day, taken as 0.2
- T = trophic (consumer) retention factor (1.2, representing a 20% conversion); (chosen as an intermediate value based on observations ranging from 0.1 to 2.4 $mg\ P/mg\ chl\ a-day$; Horner et al., 1983; Seeley, 1986)
- W = average stream width (63 m)
- B_n = nuisance threshold biomass of $150\ mg\ chl\ a/m^2$

Essentially, the equation is the ratio of SRP mass available for uptake in excess of the critical level and the expected demand for SRP by periphyton in an enriched stream reach in which the threshold nuisance biomass is attained.

Results

Phosphorus was found to be the most limiting nutrient in the lower Spokane River primarily because of the high aquifer inputs of nitrogen. The relationship between the the observed and predicted periphyton biomass as a function of the ambient SRP for artificial (20 observations) and natural substrata (21 observa-

tions), as well as data collected from natural substrata from six other streams, can be seen in Figure 1. The values for periphyton biomass (expressed as chl *a*) represent the means of 2 to 5 sampling replicates with the average replicate coefficient of variation approximating ± 50 percent.

Only eight values (four for artificial and four for natural substrata) exceeded the model predictions, and none of the values from the other six streams exceeded model predictions. When the data for the artificial and natural substrata were grouped together, there was a highly significant correlation ($P < 0.001$) between ambient S P concentrations and periphyton accrual. There was no significant correlation when the artificial and natural substrata data were treated separately. The S P concentrations during the artificial substrata collection period were lower than during the natural substrata collections and, in fact, were lower than the half-saturation value of $8 \mu\text{g/L}$. The S P concentrations may have too small to show the importance of S P as a controlling parameter; however, this also indicates that the growth-kinetic model may be a more appropriate method than the correlation analysis.

The growth kinetic model uses the physical and chemical characteristics of the river to predict algal growth and accumulation, however, periphyton losses from the grazing of macroinvertebrates are not incorporated. The impact of grazing by macroinvertebrates can be significant and has been observed to reduce the periphyton biomass as much as 80 percent (Jacoby, 1987), therefore, model predictions can be expected to exceed actual periphyton accumulation. Regardless, the model is consistent with the consensus that a threshold nuisance biomass is attainable at rather low SRP concentrations, and it suggests that there is a benefit to long-term biomass accrual at higher S P concentrations (Bothwell, 1988).

In the lower Spokane River, the nuisance threshold of $150 \text{ mg chl } a/\text{m}^2$ is exceeded at S P concentrations greater than $1.4 \mu\text{g/L}$. At these low S P concentrations, it would be difficult to control periphyton biomass through the control of SRP concentrations. The higher the S P input concentration, the greater the downstream distance will be for which S P exceeds the threshold-nuisance-saturating level before uptake lowers S P to that level. For this reason, management measures should focus on controlling the length of the stream that exceeds the biomass nuisance threshold level rather than attempt to restrict S P levels below the $1.4 \mu\text{g/L}$ range.

When Equation 2 is applied to the Spokane River, the results indicate that the stream length for which the biomass will exceed the nuisance threshold is proportional to the amount that influent SRP exceeds $1.4 \mu\text{g/L}$. Table 1 shows the pre-

Table 1. Predicted critical distances (in km) in the Spokane River for various inflow SRP_i concentrations assuming nuisance biomass levels (B_n) of 150 and 200 mg chl *a*/m² and respective SRP_i concentration ranges of 1-4 and 2-5 μ g/L.

B_n	SRP_i (μ g/L)			
	SRP_i (μ g/L)	5	10	15
150	1 - 4	2.2 - 8.7	13.0 - 19.5	23.9 - 30.4
200	2 - 5	1.6 - 5.5	8.2 - 13.0	16.3 - 21.2

(Source: Welch et al., 1989)

dicted critical distances for the lower and upper bounds of the nuisance threshold and for various inflow SRP_i concentrations.

The critical distances are rather long, indicating that perhaps a

higher threshold biomass may be the most manageable solution. It is difficult to control periphyton growth by attempting to control the limiting nutrient in flowing waters. Even at a nuisance threshold of 200 mg chl *a*/m², the critical distance would exceed 10 km, unless SRP_i is held below 10 μ g/L.

Implications

It is suggested that with some refinement, the model could be used to develop critical nutrient concentrations to control nuisance periphyton biomass in running waters. The relatively low growth-saturating concentrations of SRP makes it unlikely that controlling ambient SRP concentrations at any particular point in a stream will adequately control periphyton biomass. A more manageable parameter is the downstream distance that is adversely affected by a nutrient source. A higher nuisance biomass threshold would provide for a higher SRP_i which in turn would provide for a shorter D_c (stream length exceeding nuisance threshold). This would be particularly so in areas that have periphyton species, such as *Cladophora*, which has an uptake rate that is twice as high as the species, *Mougeotia*, which was used for this study. In addition, biomass loss from grazing may be sufficient to maintain the biomass below maximum levels. The level of grazing is dependent on the macroinvertebrate species available and the density with which they occur.

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